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SELECTION OF MATERIALS FOR SPRINGS OPERATING UNDER HIGH TEMPERATURE

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/Numbers in parentheses refer to the bibliography. Figures referred to herein are appended./

In many materials the first approximation of the relationship between stress and elastic deformation can be computed by Hooke's Law ($\sigma = E\varepsilon$), which does not give, however, a very clear picture of this relationship, being more complex than shown in the formula (1). In addition, there is no indication whatsoever of the relationship between the degree of deformation to the period of the action of stress, in spite of the fact that this relationship is very important for many parts whose elastic deformation is significant as a past or presently acting effect in the operation of machines. The chief shortcoming of Hooke's Law is that it does not take into account either elastic fatigue or elastic hysteresis (2).

In effect, if any tangible material is subjected to elastic deformation, the equilibrium produced in the elastic-deformed state can be shown by curve OAB (Figure 1). If the stress is removed, most of the elastic deformation will disappear (part BC of the curve), while the remaining deformation will disappear over a period of time at a gradually diminishing rate of speed (part C'O' of the curve on the Zε coordinate). This graph illustrates very well the existence of elastic fatigue.

Thus, if we adopt the view that elastic deformation in machine parts serves as a scale for some type of force, then the state of equilibrium will not take place immediately, but will have a slight lag (Figure 2). If, after that, the stress is increased, then the relationship can once again be represented by an almost straight extension of the graph in the original direction; however, it will coincide in places with curve BC. Elastic fatigue is even more noticeable when the part is subjected to a constant deformation. Performance of the part is affected by the resulting forces. In this event elastic fatigue inevitably results in a decrease of stress in accordance with previously determined data (Figure 3). Relaxation (lessen-

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ing) of stress is the term applied to the decrease of stress resulting from changes in elastic deformation.

Further study of this problem will show that frequently elastic deformation is transformed into plastic deformation, in which case there is no reversion to the original state. As can be seen from Figure 4, complete deformation involves: (a) pure elastic deformation (B'C'); (b) return to the original state after elastic deformation (C'D'); (c) elastic deformation which does not return to the original state (D'O).

It must be concluded, therefore, that many tangible materials possess imperfect elasticity. In such materials elastic deformation disappears only after a long period subsequent to the removal of the stress, and in some cases it does not disappear completely. This phenomenon can be explained physically by the fact that the properties of the individual crystals, containing the tangible material, are not homogeneous, and that the actual structure of the material is irregular (micro-pores, variable structural factors, intercrystallic spaces, and nonmetallic admixtures, etc.).

As a result of the imperfect elasticity of tangible materials, and the effect of temperature, machines and parts gradually lose operating power due to relaxation, particularly where clearance is an important factor in the operation of the machine (i.e. elastic deformation in coupled parts). In addition, due to the fact that temperature itself decreases the elasticity of materials, a very complex process is necessary to select those materials which will retain their elasticity even at high temperatures. To complicate matters still more, many metals develop noticeable creep at high temperatures, i.e., plastic flow due to the influence of constant stress, which also occurs as a result of decreasing stress in elastically coupled parts. However, it is important to differentiate between relaxation fatigue and relaxation creep (flow).

We can assume that in relaxation fatigue there is established some sort of a limit for stress affecting local plastic deformations. As a result of relaxation the creep stresses diminish with decreasing speed and asymptotically approach zero.

The obtained data permits the conclusion that the formation of plastic deformation in all elastically coupled parts results in the relaxation of stresses in couplings. Maxwell (3), Boltzman (4), Volterra (5) and others determined the exponential relationship of stress decreases to time in relaxation (Figure 5). A similar relationship is used to determine excessive decreases of stress during the initial period followed by a rapid, but gradually diminishing stress intensity during the subsequent period. In fact, after the completion of the intense relaxation of stress there is a gradual levelling off of the stress to some average amount, relative to the intensity of local plastic deformation caused by excess stress. As a result, there is a gradual loading of all the crystals of the metal. Consequently, the development of local plastic deformation is retarded, and the material retains an almost unchanged elastic deformation. Subsequent stresses, equal in intensity to the first stress, will not produce relaxation as intense as for the initial stress. In effect, if this experiment is performed, it will be noticed that the secondary decrease of stress will be much less, while the stability of the form resulting from stress σ'' (Figure 6) is much higher than that resulting from stress σ'.

The theoretical expressions which were developed served as the basis for solving problems with respect to technological processes in the preparation of springs which had to operate at high temperatures without losing their shape. In the past, there have been many articles which have attempted to solve individual problems in this field (6 and 7). It is now possible to draw some conclusion from all this work and to submit recommendations of a general nature regarding the selection of material, which will serve for the manufacture of springs which will function at high temperatures. These new materials must differ from conventional spring material in certain respects: (a) high resistance to creep (high thermal stability); (b) absence of tendency toward thermal frangibility; and (c) high heat resistance (high chemical stability against the effect of aggressive gases at high temperatures).

These requirements can be met by selection of materials with proper chemical

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properties. Stability of spring shapes, which are characterized by small relaxation speeds, can be obtained by supplementary processing which will prevent extreme relaxation of the springs under operational conditions. Therefore, in the manufacture of springs it is necessary to prevent deviation from measurements computed for proper operation of the springs (for example, the distance between the shackles on compressed springs). However any deviation from the standard should be such that after supplementary heat treatment for anticipated relaxation (retention of elasticity after being subjected to stress for a period of 24 to 30 hours after heat treatment they would disappear completely due to the conversion of elastic deformation into plastic deformation. The object of this operation is to produce an initial intense and complete relaxation cycle in the unit with a subsequent slower change of the elastic deformation into plastic deformation, without any serious effect on the performance of the unit. This is confirmed by the fact that the secondary increase of stress permits the use of fairly large stresses (however not above those acting during the initial relaxation) with only very small subsequent changes in the shape of the springs. Consequently, the technological process for the preparation of springs which are intended for operation at high temperatures includes the following stages: (a) manufacture of the springs (particularly the coil type); (b) ordinary heat treatment (annealing and tempering); (c) initial relaxation under actual operating conditions (retention of elasticity after being subjected to stress for 24 to 30 hours at ordinary operating temperatures); and (d) acceptance tests (in particular, tests for sturdiness)

The theory (8) that it is possible to use temperatures higher than ordinary operating temperatures during the initial relaxation is erroneous. In many cases, the interval between the annealing temperature and the relaxation temperature (i.e., the operating temperature) is so small that it is not possible to produce the initial relaxation at high temperatures with the objective of shortening the elasticity retention test without lowering the elastic limits of the spring material. This lowering of limits will be noticed in the acceptance tests or will be reflected in the operation of the springs (possibility of having them lose their resilience more quickly, due to the lowering of the elasticity limits).

In accordance with requirements, the chemical standards for steels used in the manufacture of springs must include the following factors:

1. An increased amount of carbon (0.5 percent or more) to obtain high enough rigidity
2. Chromium or silicon admixtures to narrow the ratio between the limit of proportionality and the limit of stability to unity; these admixtures also increase the heat resistance of the steel
3. Tungsten, molybdenum, vanadium and chromium admixtures to increase the heat resistance of the steel
4. Increasing the amount of manganese and nickel facilitates drilling holes in the springs; particularly desirable where springs are manufactured from materials having large cross sections

The work conducted to determine the best type of steels for springs which have to operate at high temperatures formed the basis of the following tables.

Table 1. Recommended Steel Types for Springs Operating at High Temperatures

Chemical Composition (in Percent)

Type of Steel	C	Si	Cr	Other Elements	Temperature Limits (degrees centigrade)
60S2	0.55-0.65	1.5-2.0	-	-	Up to 250
40KhS	0.35-0.45	1.2-1.6	1.3-1.6	-	
50KhF	0.46-0.54	-	1.3-1.6	0.15 V	250 to 350
Zh3	0.24-0.35	-	12.0-14.0	-	350 to 400
Zh4	0.35-0.45	-	12.0-14.0	-	
60Kh16 M2A	0.50-0.70	-	15.0-17.0	1.5-2.5 Mo	400 to 500
EI290	0.95-1.07	-	3.7-4.4	2.7-3.3 Tungsten 2.7-3.0 Mo 1.5-2.0 Vanadium	500 to 600

NOTE: The elements which do not affect the characteristics of the given steels are in accordance with established state standards.

There is no doubt that there are other steels which can be easily used for the production of springs intended for operation at high temperatures.

Table 2. Heat Treatment of Steels for Springs Operating at High Temperatures

Type of Steel	Tempering (degrees centigrade)	Recommended Procedure: Materials used for Quenching	Recommended Procedure: Annealing (degrees centigrade)	Relaxation (degrees centigrade)
60S2	880-900	Oil	350	250
E4Khs	840-860	"	450	370
E5KhF	840-860	"	450	370
Zh3	1020-1050	"	530	420
Zh4	1020-1050	Air	530	420
60Kh16M2A	1100-1200	Oil	600	520
EI290	1180-1220	"	650	600

Nevertheless, because of the very complex nature of the problem, it is necessary to make a thorough examination of the steels before making any definite recommendations. This examination should include the mechanical properties of steels at high temperatures, as well as the determination of the best methods for obtaining the initial relaxation of steels. So far, it has been a generally accepted fact that high speed steels are the best materials for springs, as they have the best heat resistance. However, on the basis of experiments, cobalt and some austenite alloy steels can also be recommended.

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[Figures follow]

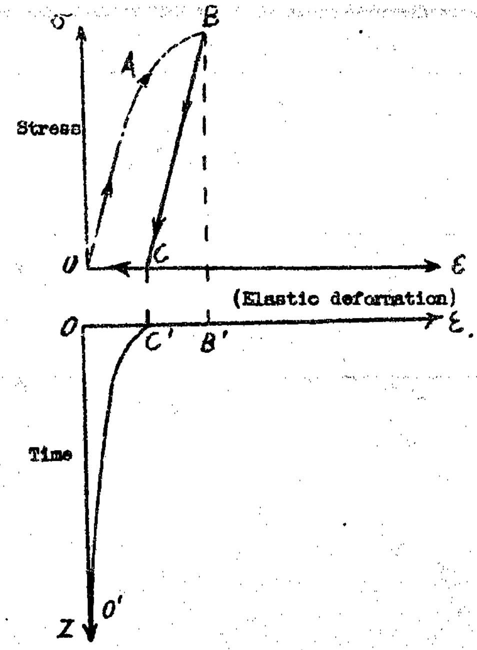

Figure 1. Equilibrium Produced by Elastic Deformation

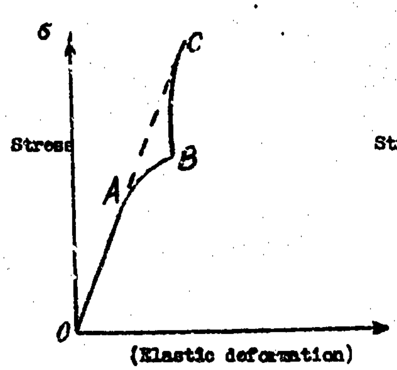

Figure 2. Lagging Equilibrium During Elastic Deformation, Acting as a Scale for any Force

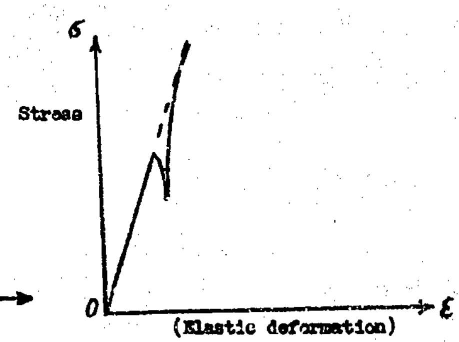

Figure 3. Decreasing Stress, due to Elastic Fatigue, Compared With Fixed Stress

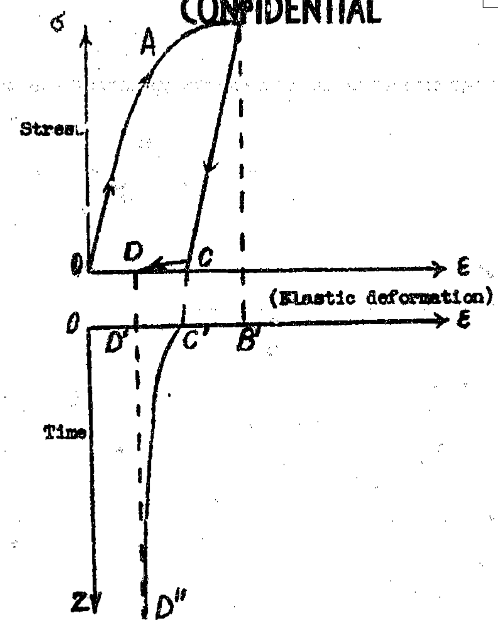

Figure 4. Conversion of Elastic Deformation Into the Plastic and Completely Deformed State

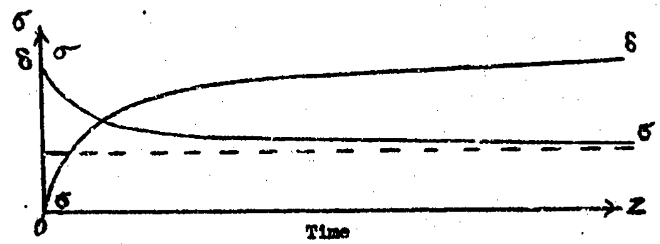

Figure 5. Exponential Decrease of Stress With Reference to Time During Relaxation

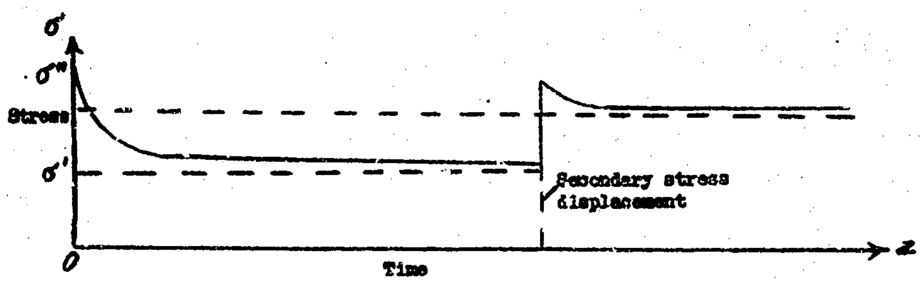

Figure 6. Secondary Decrease of Stress and Stability of Shape

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